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Concepts for Lift Improvements of a High-Lift Military Airfoil

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Abstract

This paper describes the computational analysis of several concepts to improve the maximum lift of a military high-lift airfoil configuration. The computational results are compared with the wind-tunnel data obtained for a gap and overhang study and a Gurney flap study. In the wind tunnel experiments, optimizing the gap and overhang and adding a Gurney flap provided the largest increases, on the order of 3-4%. These trends were duplicated in the CFD analyses. Incremental lift improvements were found using the Gurney flap and by adjusting the gap and overhang of the flap. Lift improvement was also obtained by perturbing the leading edge portion of the trailing edge flap. It was found that the lift enhancements were additive, the maximum lift increased by 14% using a Gurney flap and the flap at the optimum gap and overlap. The CFD analyeses used an unstructured Navier-Stokes code. The wind tunnel tests were a cooperative effort between the Navy, Boeing (St Louis), and NASA LaRC and were conducted in the NASA Langley Research Center (LaRC) Low Turbulence Pressure Tunnel (LTPT) . Forces and moments and other parameters were measured on a two dimensional (2-D) airfoil model of a advanced fighter wing section configured with a deflected leading edge flap, shroud and a slotted trailing edge flap.

Nomenclature

C	Clean Airfoil Chord
c_l	Lift Coefficient
c_{lmax}	Maximum Lift Coefficient
Gap	Flap Gap (% C)
LEF	Leading Edge Flap
M	Mach Number
O.H.	Flap Overhang (% C)
TEF	Trailing Edge Flap
X/C	Nondimensional Chord
Y/C	Nondimensional Span
y^+	Sublayer-Scaled Distance
α	Angle of Attack (Deg.)
δ_f	Trailing Edge Flap Deflection Angle (Deg.)
δ_n	Leading Edge Flap Deflection Angle (Deg.)
δ_s	Shroud Deflection Angle (Deg.)

Introduction

Additional multi-mission operational demands placed on the Navy high performance aircraft have resulted in increase in the carrier-approach speed over the last several decades. High approach speeds have been shown to be directly correlated to reduced operational safety and increased maintenance and life cycle cost. It has become very important to study and improve the high-lift systems in order to reduce the approach speeds and thus improve safety of the flight operations from a carrier deck. The Navy depends on low-speed high-lift aerodynamics, to enable high performance multi-role strike/fighter aircraft to operate from a carrier deck.

Leading edge shape, and airfoil thickness are the two major geometric differences that distinguish modern high performance multi-role strike/fighter military airfoils from commercial configurations. Sharp leading edges are driven by integration of stealth requirements and thin airfoils with thicknesses of the order of 5-8% chord are dictated by supersonic efficiency requirements. A typical military airfoil configuration along with nomenclature and the flow physics in-

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volved is shown in Fig. 1.

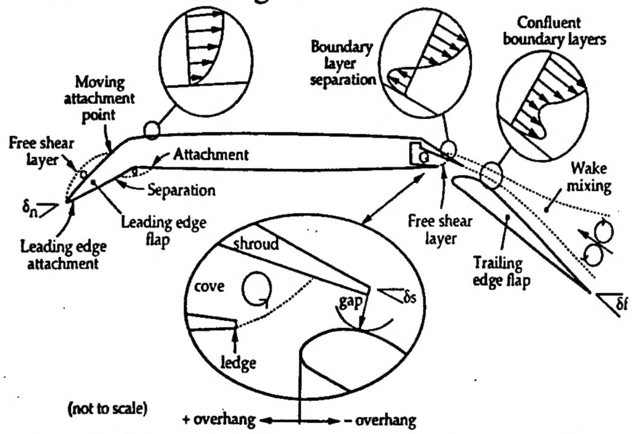

Fig.1 Military high-lift multi-element airfoil

Flap gap and overhang and high lift system design conducted at sub-scale Reynolds numbers may not remain optimal at flight Reynolds numbers.[1] These effects can become pronounced in three dimensional flows due to the mechanisms of attachment line transition, re-laminarization, and vortical flow interactions on the three dimensional wings of military aircraft. Typical aircraft development programs rely on sub-scale Reynolds number wind tunnel data to design high-lift systems, with empirical corrections for the Reynolds number effects. These methods do not account for three-dimensional effects and are based on conventional designs, and therefore are not accurate enough to guarantee several performance issues. There is motivation, therefore, to develop CFD methods to accurately predict maximum lift as well as post stall aerodynamic characteristics for high lift configurations. Once validated for a class of configurations and flow conditions, the vision is that CFD could be used to 1) complement wind tunnel data, 2) provide the ability to optimize component rigging and shape at flight Reynolds numbers, 3) provide the ability to correct small-to-moderate scale wind tunnel data for Reynolds number and wind tunnel wall and support system interference effects and 4) provide support in designing subcomponents.

The Navy's interest in this project has been to investigate the physics of the flow field and to seek additional concepts to improve the high-lift system. The focus of the current effort was to investigate concepts to achieve higher lift coefficients for a high-lift configuration. The following concepts were found useful in enhancing the lift coefficients. Gurney flaps, reshaping of the upper surface of the leading edge segment of the trailing edge flap and optimization of flap gap and overhang ratios. A computaional study of the variation of the $c_{l_{max}}$ with gap and overhang was performed and the computational trend towards the optimum gap and overhang agreed fairly well with the experimental results.

Unstructured Navier-Stokes Solutions

Recently, unstructured grids have been explored for the solution of CFD problems. This approach has several advantages over structured grids for problems that involve complex geometries and flows. One of the main advantages is the reduction in time needed to generate grids around a complex configuration.

Grid Generation

A two-dimensional viscous unstructured grid generator, TRI8IT was used to generate the grid around the multi-element airfoil. This program triangulates a multiply-connected domain using an incremental point insertion and a local edge-swapping algorithm. In the first step an initial triangulation is used as a framework for constructing contours of a field variable which is a measure of the distance from the field point to the nearest point on the airfoil surface. Level curves are constructed using three input parameters which govern the geometric stretching and spacing between the contour levels. After the level curves are generated a new triangulation process is initiated followed by insertion of airfoil points and field points along the level curves by projecting points outward from one level curve to the next. This process continues until the last level curve is reached and the grid generation process is complete. A perl script is used to generate a sequence of coarse to fine grids automatically for multigrid applications.

<u>Unstructured Grid</u>

The input to TRI8IT is the y+ value, the number of coarser grids to be generated after the fine grid and the outer boundary distance. Initially the outer boundary was set at 15 chord lengths. To get a converged solution, the outer boundary was set at 7 chord lengths. For the baseline high-lift military airfoil, with $y^+ = 1$, the first mesh was specified at .000002837 chord lengths above the surface of the airfoil and a geometric stretching ratio of 1.14 was specified for the computational grid. For the baseline configuration, the mesh contained about 72,000 points with about 150,000 triangles, Fig. 2. Each change in the gap and overhang resulted in a small change in the number of points and triangles over the baseline configuration. The mesh, corresponding to the Gurney flap configuration, contained about 80,000 points and about 160,000 triangles, Fig. 3.

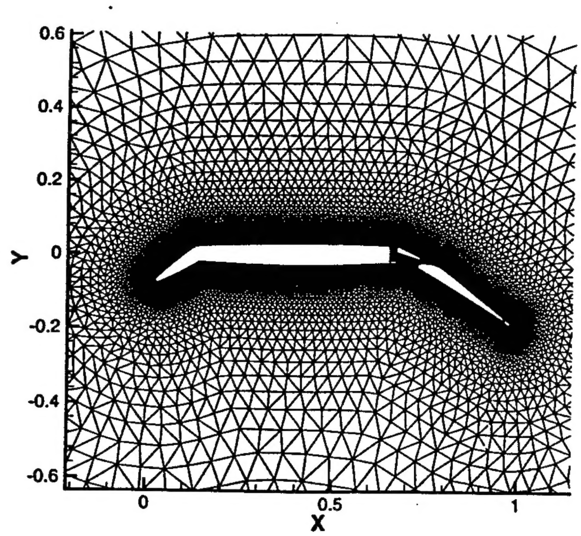

Figure 2. Unstructured 2D mesh around airfoil

<u>Solution Method</u>

FUN2D was used to calculate the flow solutions around the high-lift airfoil. FUN2D solves the Reynolds averaged Navier-Stokes equations with the one equation turbulence model of Spalart-Allmaras[4] (SA) model. The flow solver is an implicit upwind algorithm in which the inviscid fluxess are obtained on the faces of each control volume with a flux-difference - splitting scheme. A node based scheme is used and the equations are sorted at the vertices of the grid and the equations are solved on non-overlapping control volumes that surround each node. The viscous terms are evaluated with a finite-volume formulation that is equivalent to a Galerkin type of approximation for these terms. The solution at each time step is updated with the linearized backward Euler time-differencing scheme. At each time step, the linear system of equations is approximately solved with either a point implicit method or the generalized minimal residual (GMRES) method. A multigrid method is used to accelerate the convergence of the solution.

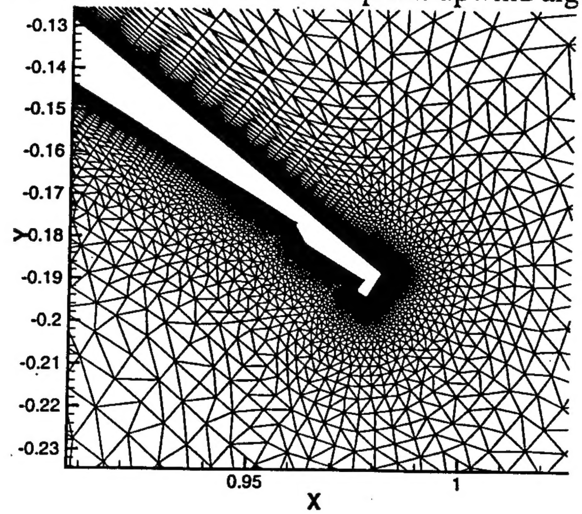

Figure 3. Unstructured 2D mesh around Gurney flap, configuration GF1.

All the CFD solutions were generated at M=0.2 and fully turbulent flow was imposed everywhere. The computational results correspond to the highest Reynolds number of 16 million. All the cases analyzed utilized multi-grid solutions technique with mesh sequencing and in all most all the cases the computations were run till the errors reduced by about 3 orders of magnitude.

Wind-Tunnel Tests

Wind tunnel tests were conducted in the NASA langley Research Center (LaRC) Low Turbulence Pressure Tunnel (LTPT) as part of a cooperative effort between the Navy, McDonnell Douglas Aerospace (now Boeing) and NASA LaRC. Surface pressures, forces and moments, were measured on a two dimensional (2-D) airfoil model of a Boeing advanced fighter wing section configured with a deflected leading edge flap, shroud and a slotted trailing edge flap. Results from these tests have been reported in previous papers[2,3].

A detailed account of the LTPT test facility and the description of the high-lift airfoil model can be found in Ref. 2. The model had a 3 ft. span and 22 inch chord and was mounted 6 inches above the centerline of the 3 ft. wide, 7 ft. tall test section. The computational results are compared with the data set with the deflections of the LEF, TEF and the shroud set at 34^o, 35^o, and 22.94^o respectively representing a landing configuration. Pressure and force data due to variations in gap and overhang parameters, Table 1, were obtained. The baseline configuration was set with overhang and gap of 2.66%C and 0.512%C respectively.

Table 1. Experimental Parametric overhang and gap settings, total 9 configurations

O.H. in%C	Gap in%C
2.66*	**0.512***
1.756	0.522
2.756	0.522
3.756	0.522
1.756	1.085
2.756	1.085
3.756	1.085
1.885	0.799
2.885	0.799
3.885	0.799

Two sets of Gurney flaps, Fig. 1, were attached separately at various positions on the lower moldline of the trailing edge flap. The small Gurney flap (configuration GF3) was located along the trailing edge of the TEF. The large Gurney flap was located along the trailing edge of the TEF (GF1), one "pad length" forward of the trailing edge (GF4) and two "pad lengths" forward of the trailing edge (GF2). The height of the large Gurney was 0.6% of the chord and for the small Gurney the height was 0.3% of the airfoil chord.

The tests were conducted at Reynolds numbers from 5, 9 and 16 million at the Mach number of 0.2 and at a range of angles of attack. Side wall boundary layer control system helped to ensure 2-D flow. When the spanwise pressures deviate beyond the acceptable tolerance level, the side wall suction was adjusted to ensure 2-D flow. Since the side wall vents are metric, there was a lack of confidence in the accuracy of the measured balance data. Therefore, to obtain lift, the pressures measured by surface pressure taps were integrated. Lift was not corrected for wind tunnel effects, since a previous study investigating wall effects on a commercial configuration concluded that these effects were minimal at lift coefficients below 2.5[5].

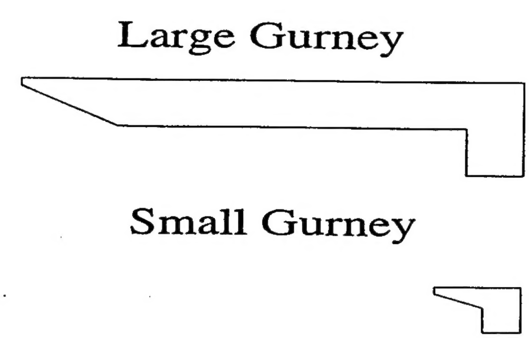

Figure 3. Gurney Flaps used in the Wind Tunnel Experiments. Height of Large Gurney was 0.6%C .Height of Small Gurney was 0.3%C.

Discussion

In the wind tunnel, several different overhang and gap combinations for the baseline configurations were tried at the Reynolds numbers of 5 and 16 million[3]. The data with Gurney flaps attached at the trailing edge to the baseline configuration were also obtained at these Reynolds numbers. The effects of the variation in the gap and overhang and Gurney flaps at the Reynolds number of 5 and 16 million were performed in the wind tunnel. Out of several overhang and gaps, overhang and gap of 1.085% and 1.756% respectively provided the maximum increase of 3% in c_{lmax} over the baseline case as seen in the Fig. 4. The maximum increase in c_{lmax} due to the large Gurney flap attached to the baseline configuration on the lower surface of the TEF is also shown in the same figure. The Gurney flaps produced increase in c_{lmax} of about 4% which amounts to roughly about 2% reduction in approach speed. As discussed in Ref. 3, the vortex generators improved the lift by a small amount.

The computational results for the high-lift configuration will be compared with the wind-tunnel test results. All the computational calculations were done at the flight Reynolds number of 16 million and with a fully turbulent boundary layer.

Computational Results of the Variation of Gap and Overhang

The matrix of overhang and gap ratios for the computational analysis is shown in Table 2. Unlike Table 1 which gives the gap and overhang combinations, Table 2 represents, in effect, the rows and columns of the configuration matrix. For the CFD analysis, 35 configurations of gap and overhang were analyzed for each angle of attack at the flight Reynolds number of 16 million.

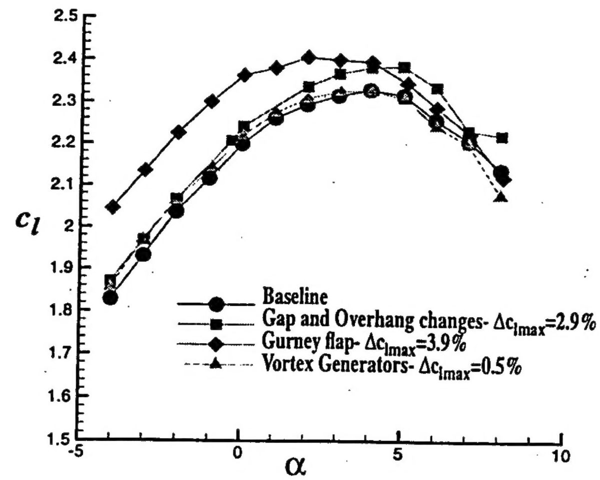

Figure 4. The effects of gap and overhang, Gurney flap and vortex generators on c_l.

Table 2. CFD Parametric overhang and gap settings, 35 total configurations

O.H. in %C	Gap in %C
2.66*	**0.512***
2.16	1.012
1.66	1.512
1.16	2.012
0.66	2.512
0.16	3.012
-.34	-
-1.34	-

Contours of the maximum lift with overhang and gap from the wind-tunnel results are presented in Fig. 5. The contours from the computational analysis are presented in Fig. 6. From both set of contours it is seen that the lift increases as the overhang reduces and the gap increases. For the wind-tunnel data, the extent of the gap and overhang changes were not

enough to reveal the complete details of the contour shape and maximum lift position. The CFD analyses does a good job covering the range of gap and overhang required to reveal the approximate shape of the contour and approximate location of the maximum $c_{l_{max}}$ for this airfoil configuration. The computational results are consistent with this type of slotted flap[6]. For the flap at the optimum position (OPT), the maximum lift increases by 11.1% as compared to the flap at the nominal position (NOMINAL).

It must also be pointed out that the viscous flow physics can be very different from one overhang gap combination to another combination and varies in a nonlinear way. Although this effect does not show up clearly in the contour plots, at the largest gap and moving from larger to smaller overhang there is a large change in the lift due to separation of the flow from the flap.

There is always a possibility of having a local optimum and not a global optimum by the kind of approach we have taken in the present analysis. A rigorous mathematical search procedure with CFD solution interaction at each overhang and gap design space is desirable. Such interactive procedures are very costly and extremely time intensive, but nevertheless they have advantages of bearing accurate optimum solutions. Such solution procedures are being developed at Navy and will be the subject of future investigations.

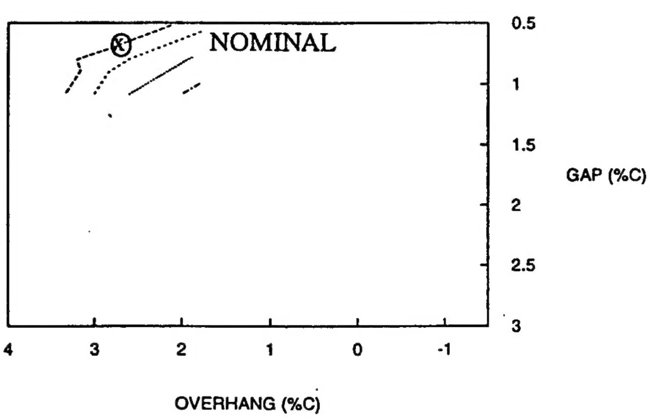

Figure 5. Gap and overhang contours of wind-tunnel maximum lift coefficients. Contours: _._._. $c_l = 2.36$, ... $c_l = 2.34$, - - - $c_l = 2.32$, ----- $c_l = 2.3$. Original flap position is at NOMINAL.

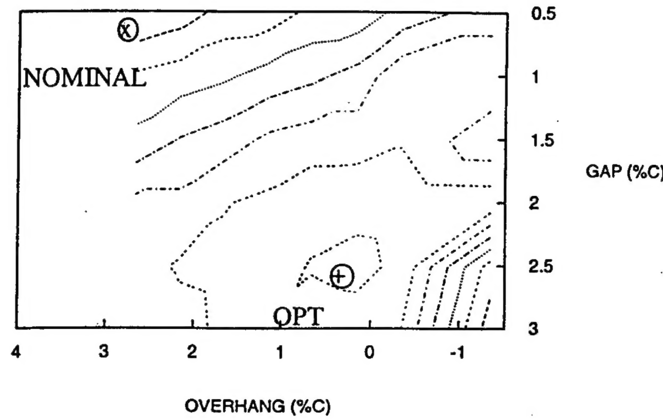

Figure 6. Gap and overhang contours of CFD maximum lift coefficients. Contours:--- ---$c_l = 2.62$,-- --$c_l = 2.60$,_ . _ .$c_l = 2.58$, _._._. $c_l = 2.56$, ... $c_l = 2.54$, - - - $c_l = 2.52$, ----- $c_l = 2.5$. Original flap position is at NOMINAL, optimum flap position is estimated to be at OPT.

<u>Computational Simulation of the Gurney Flaps</u>

Next the effect of the Gurney flaps are considered and the lift coefficients obtained using CFD are compared with the experimental results. Only the large Gurney at the end of the trailing edge flap, configuration GF1, was analyzed.

This Gurney configuration resulted in a maximum lift enhancement of 4.8%, Fig. 7. Higher suction on the upper surface and hence a higher circulation was generated for all the angles of attack. This led to lift improvement at all the angles of attack. The higher circulation is shown in Fig. 8 for an angle of attack of 2 degrees.

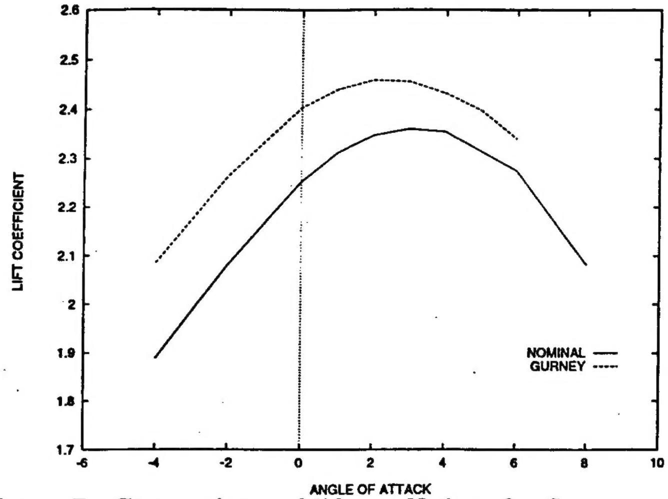

Figure 7. Comparison of lift coefficient for flap with Gurney, GF1, with original, NOMINAL, flap. Lift enhancement of 4.8%

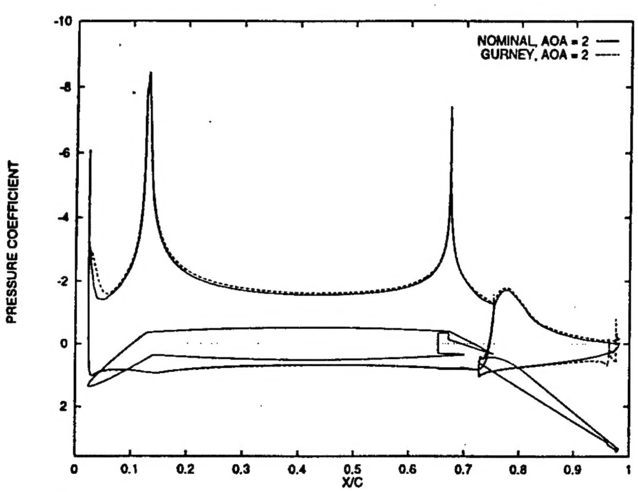

Figure 8. Comparison of pressure coefficient for trailing edge flap (NOMINAL) and flap with Gurney, GF1, at nominal position.

Since there have been no similar studies for Gurney flaps, to the best of our knowledge, there is no direct comparison for our results. A study[7] of a 14% thick, natural laminar airfoil and Gurney flaps demonstrated a similar general increase in the circulation at all angles of attack. Larger Gurney flaps were considered, 3.3%C and 1.5%C. A much larger increase in the lift at a given angle of attack and a much larger increase in the maximum lift were observed. Our results are consistent that Gurney flaps can increase the airfoil circulation and increase the maximum lift coefficient.

Perturbation of the Leading Edge of the Trailing Edge Flap

Another concept, to enhance the lift, was to reshape the leading edge portion of the upper surface of the flap. It was found that a vortex was created which in turn created an additional suction producing a lift increase.

To create minimal impact on the other constraints of the airfoil, a small leading edge portion of the upper surface of the trailing edge flap was perturbed and the effects of the change on the c_{lmax} were computationally studied. Out of several configurations tried, only the MOD2 configuration showed an increase in the lift. The configuration MOD2 compared with the original leading edge is shown in Fig. 9. The lift curve that was generated by the airfoil with the MOD2 flap leading edge is shown in Fig. 10. A maximum-lift enhancement of about 1% was obtained.

An interesting discovery was that the effect of perturbing the leading edge produced a vortex. Streamlines near the leading edge of the flap are shown in the Fig. 11. A small vortex is clearly seen in the immediate vicinity of the leading edge on the upper surface of the flap. This vortex results in increased suction on the upper surface compared to baseline configuration as seen in Fig. 12.

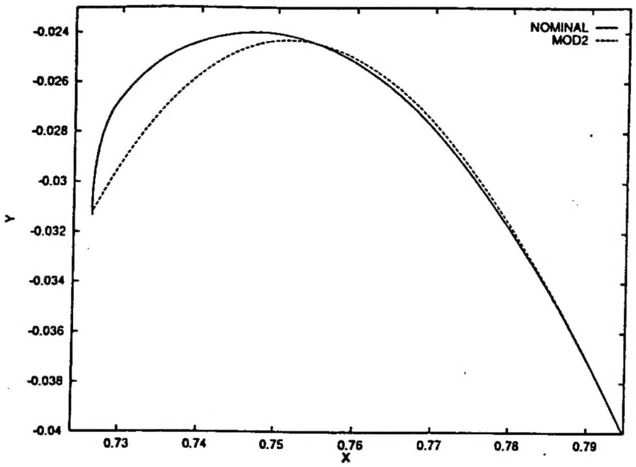

Figure 9. Comparison of new flap leading edge geometry, MOD2, with original, NOMINAL. Extent of change is about 20% of upper surface relative to the flap chord.

As pointed out, changes in the lift from the baseline configuration were sensitive to the changes in a small portion of the upper surface from the leading edge of the flap. An automatic optimization technique would be very useful to find the optimum shape of the flap to produce a positive lift increase. Indeed, such a procedure is already under preparation in the Navy under a different program.

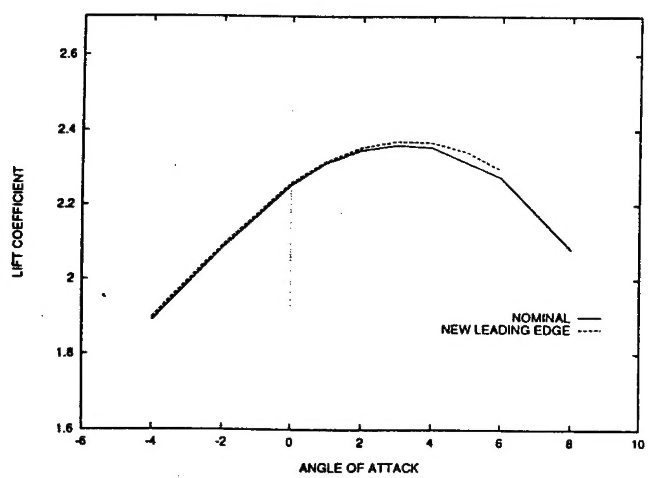

Figure 10. Lift curve MOD2 leading edge compared to original (NOMINAL). Lift enhancement of about 1%.

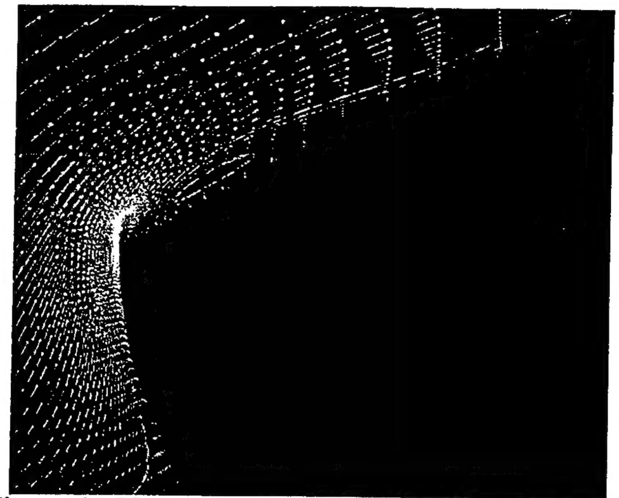

Figure.11 Vectors near the leading edge of the "MOD2" trailing edge flap

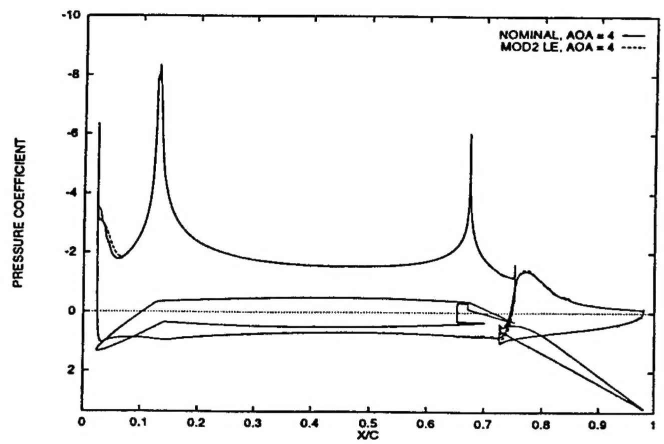

Figure 12. Comparison of pressure distributions for NOMINAL flap and MOD2 leading edge modification.

Superposition of the Concepts

Till now, several concepts such as Gurney flaps, optimum overhang and gap parameters and perturbation of leading edge surface were considered which produced positive lift increments. At this time an interesting question arises: Will a combination of one or two of the concepts described above lead to a favorable effect? A preliminary computations with

some of the concepts indicated that two concepts added on the baseline configuration would, indeed, produce the combined effect of the individual effects.

The combined effect of increase in lift was verified, Fig. 13. The optimum choice of overhang and gap and the Gurney flap produced a positive lift increases of about 11% and 5% respectively.

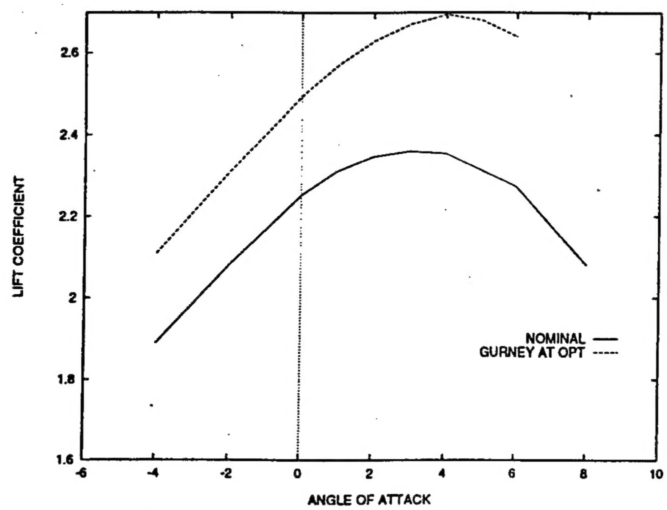

Figure 13. Comparison of lift coefficient for flap with Gurney, GF1, at optimum position with original flap and flap location. Maximum lift enhancement of about 14%.

Moving the trailing edge flap with the gurney (GF1) to the approximate (CFD predicted) optimum position resulted in a total lift enhancement of 14.2%, Fig. 13. In this configuration in addition to the higher circulation at all angles of attack, there was a significant increase in lift on the trailing edge flap due to the optimum position of the flap, Fig. 14.

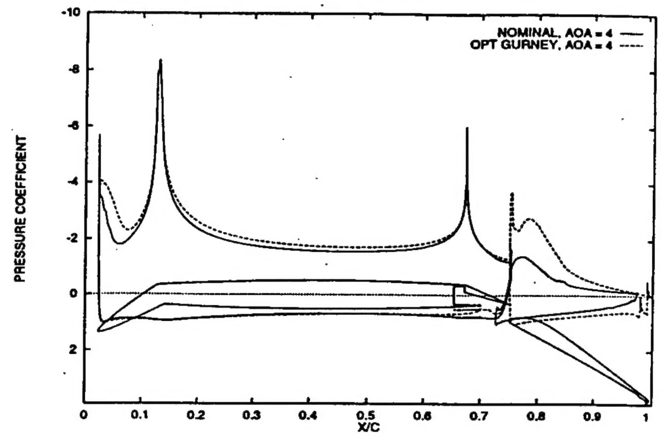

Figure 14. Comparison of pressure coefficient for NOMINAL trailing edge flap and flap with Gurney GF1 at optimum position, OPT GURNEY.

From this simple calculation it seems that it may be possible to get lift increases through the additive effects of the favorable concepts.

Summary

Several concepts to improve the maximum lift of the high-lift configuration were tried in the wind tunnel. Of these, optimizing the gap and overhang and adding a Gurney flap provided the largest increases, on the order of 3-4%. These trends were duplicated in the CFD analyses. As a result CFD was used to predict the effect of other lift enhancements. By optimizing the flap gap and overhang, an increase in lift of 11% may be possible. Adding a Gurney flap to the optimum configuration gains an additional 3%. By perturbing the leading edge of the TEF, additional lift enhancements may be obtained. We found that the lift enhancements were to a certain extent additive.

Acknowledgments

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Ames.

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